

# The thermodynamics of a gravitating vacuum

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**Abstract** In the present days of modern cosmology it is assumed that the main ingredient to cosmic energy presently is vacuum energy with an energy density  $\epsilon_{vac}$  that is constant over the cosmic evolution. In this paper here we show, however, that this assumption of constant vacuum energy density is unphysical, since it conflicts with the requirements of cosmic thermodynamics. We start from the total vacuum energy including the negatively valued gravitational binding energy and show that cosmic thermodynamics then requires that the cosmic vacuum energy density can only vary with cosmic scale  $R = R(t)$  according to  $\epsilon_{vac} \sim R^{-\nu}$  with only two values of  $\nu$  being allowed, namely  $\nu_1 = 2$  and  $\nu_2 = 5/2$ . We then discuss these two remaining solutions and find, when requiring a universe with a constant total energy, that the only allowed power index is  $\nu_1 = 2$ . We discuss the consequences of this scaling of  $\epsilon_{vac}$  and show the results for a cosmic scale evolution of a quasi-empty universe like the one that we are presently faced by.

**Keywords** Cosmic vacuum energy density – Friedmann equations – Thermodynamics

## 1 Introduction

We start this paper asking why at all should a vacuum gravitate or influence spacetime geometry? This question is perhaps worth to be asked, since, if vacuum, *expressis verbis*, represents 'nothing' in a physical sense,

then it should not do anything, especially should not gravitate, unless it is wrongly defined. Modern physics nowadays argues, however, that a vacuum cannot be energy-less, but is loaded with energy, or, due to the energy-mass equivalence, is mass-loaded. Masses, on the other hand, do in general gravitate, unless something else compensates for that. But how could sources of gravity be compensated, unless perhaps by anti-masses which are not known to exist?

The General Relativistic action of a vacuum in general is taken into account by a fluid-like hydrodynamical energy-momentum tensor  $T_{\mu\nu}^{vac}$  which describes how the vacuum, due to its pressure  $p_{vac}$  and its mass energy density  $\rho_{vac}$ , acts as source of spacetime geometry (see e.g. Goenner 1996). If in addition vacuum energy density  $\epsilon_{vac} = \rho_{vac}c^2$  is assumed to be constant, as done in present-day standard cosmologies (see Perlmutter et al. 1999; Bennett & Halpern 2003), then this induces the relation  $p_{vac} = -\epsilon_{vac}$  (see e.g. Peebles & Ratra 2003) and leads to the following geometrical source tensor (see e.g. Overduin & Fahr 2003)  $T_{\mu\nu}^{vac} = \rho_{vac}c^2 g_{\mu\nu}$ , where  $g_{\mu\nu}$  denotes the metric tensor.

This term  $T_{\mu\nu}^{vac}$ , since being isomorphical, can be taken together with the term due to Einstein's cosmological constant  $\Lambda_0$  (Einstein 1917). If both terms are placed on the right-hand side of the GRT field equations, while Einstein placed his term on the left hand side, they can be put together representing an 'effective' cosmological constant  $\Lambda_{eff}$  given by (Overduin & Fahr 2001; Fahr 2004)

$$\Lambda_{eff} = \frac{8\pi G}{c^2} \rho_{vac,0} - \Lambda_0. \quad (1)$$

Now one can draw the following conclusion: A completely empty, matter-free space, not doing anything in terms of gravity, is realized, if, evident from the above,  $\Lambda_{eff}$  just vanishes, i.e. the cosmological term  $\Lambda_0$  just

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compensates the vacuum energy density of empty space whatever maybe its value (e.g. see Zeldovich 1968; Carroll, Press & Turner 1992).

Interestingly, very similar ideas have come up in papers by Sola (see Sola, 2013, 2014) who expresses the fact that in order to settle down the spacetime geometry of a pure vacuum to a nongravitating Minkowskian spacetime within a covariant general-relativistic field theory the effective vacuum energy of this empty space has to vanish.

In the presence of real matter the argumentation, however, is much more complicate as we have discussed at several places in the literature (Overduin & Fahr 2001; Fahr 2004; Fahr & Heyl 2007a, 2007b; Fahr & Sokaliwska 2012). Especially it is then highly questionable whether under such conditions a constant vacuum energy density can at all be expected as an option.

If under these perspectives it could be assumed, that only the energy difference between the matter-polarized and the empty vacuum gravitates then some interesting new conclusions could be drawn. It then means that in a matter-filled universe the effective quantity representing the action of the vacuum energy density is given by:

$$\Lambda_{eff} = \frac{8\pi G}{c^2}(\rho_{vac} - \rho_{vac,0}). \quad (2)$$

The above formulation expresses that in a matter-filled universe only the difference between the values of the vacuum energy densities  $\rho_{vac,0}$  of empty space and  $\rho_{vac}$  of matter-polarized space gravitates, i.e. the spacetime geometry only reacts to the difference of these vacuum energies.

Even under these new prerequisites it is nevertheless not the most natural assumption, that vacuum energy density  $\epsilon_{vac} = \rho_{vac}c^2$  should be considered as a time-independent quantity. This is because the unit of volume is not a cosmologically relevant quantity, and vacuum energy density neither is. It would probably appear more reasonable to assume that the energy load of any homologously comoving proper volume does not change with cosmic expansion, i.e. that rather just this proper-energy is constant. This demand, however, means that the true constant quantity, instead of the vacuum energy density  $\epsilon_{vac}$ , is

$$e_{vac} = \epsilon_{vac}\sqrt{-g_3}d^3V \quad (3)$$

where  $g_3$  is the determinant of the 3d-space metric which in case of a Robertson-Walker geometry is given by

$$g_3 = g_{11}g_{22}g_{33} = -\frac{1}{(1-Kr^2)}R^6r^4\sin^2\vartheta \quad (4)$$

with  $K$  denoting the curvature parameter, the  $R = R(t)$  determining the time-dependent scale of the universe, and the differential 3-space volume element in normalized polar coordinates given by

$$d^3V = drd\vartheta d\varphi. \quad (5)$$

This then leads to the following request

$$\begin{aligned} e_{vac} &= \epsilon_{vac}\sqrt{R^6r^4\sin^2\vartheta/(1-Kr^2)}drd\vartheta d\varphi = \\ &\epsilon_{vac}\frac{R^3}{\sqrt{1-Kr^2}}r^2\sin\vartheta drd\vartheta d\varphi = const. \end{aligned} \quad (6)$$

which evidently leads to a variability of the vacuum energy density  $\epsilon_{vac}$  in the form

$$\epsilon_{vac} = \rho_{vac}c^2 \sim R(t)^{-3}. \quad (7)$$

In the following paper we shall now throw some new light on the variability of  $\epsilon_{vac}$  that must be expected. We therefore study the behavior of the vacuum energy density  $\epsilon_{vac}$  with the scale  $R(t)$  of the universe from a thermodynamical view.

## 2 Thermodynamics of the cosmic vacuum

In the following cosmological considerations we treat the cosmic vacuum by quantities denoting its vacuum energy density  $\epsilon_{vac}$  and its associated vacuum pressure  $p_{vac}$ , like done in case of a hydrodynamic fluid which in general relativity theory is described by the following fluid-type hydrodynamical energy-momentum tensor (see e.g. Goenner 1996; Overduin & Fahr 2001; Blome, Hoell & Priester 2002; Fahr 2004)

$$T_{\mu\nu}^{vac} = (\rho_{vac}c^2 + p_{vac})U_\mu U_\nu - p_{vac} * g_{\mu\nu} \quad (8)$$

where  $\epsilon_{vac} = \rho_{vac}c^2$  and  $p_{vac}$  are energy density and pressure of the vacuum,  $U_i$  denote the components of the fluid four-velocity, and  $g_{\mu\nu}$  is the four-space metric tensor.

In order to use the above energy-momentum tensor in the frame of the general relativistic field equations

one needs to know, how  $\rho_{vac}$  and  $p_{vac}$  are related to each other and how they are dependent on spacetime coordinates. For that purpose we want to use the well known thermodynamic equation that relates the internal volume energy with the work expended at the expansion of that volume. In its easiest form for a Robertson-Walker symmetric universe with curvature  $K = 0$  this equation for a sphere of scale  $R = R(t)$  is given by (see Goenner 1996):

$$\frac{4\pi}{3} \frac{d}{dR} (\varepsilon_{vac} R^3) = -p_{vac} \frac{4\pi}{3} \frac{d}{dR} R^3. \quad (9)$$

Analogously to a star at its contraction the internal volume energy, irrelevant whether it is vacuum- or matter-filled, should, however, be completed by the gravitational self-binding energy, since a vacuum that is energy-loaded evidently is a source of internal gravity which at all makes it cosmologically relevant as source of cosmic geometry. If we include the negatively valued gravitational self-binding energy (see Fahr & Heyl 2007a, 2007b) into the total internal energy of a cosmic sphere with radius  $R$ , then instead of the above relation one obtains the following more complicate thermodynamic equation:

$$\frac{d}{dR} \left[ \frac{4\pi}{3} \varepsilon_{vac} R^3 - \frac{8\pi^2 G}{15c^4} (\varepsilon_{vac} + 3p_{vac})^2 R^5 \right] = -p_{vac} \frac{4\pi}{3} \frac{d}{dR} R^3 \quad (10)$$

which now instead of Eq. (9) should define the relation between  $\varepsilon_{vac}$  and  $p_{vac}$  and both their dependences on the scale parameter  $R = R(t)$  which is a function of the cosmic time  $t$ .

As evident, in this highly symmetric FLRW universe both quantities, i.e.  $\varepsilon_{vac}$  and  $p_{vac}$ , can only depend on the scale parameter  $R(t)$ . We now try to solve the above equation, following the same way as already used in the case of the more simple, uppermost thermodynamic Eq. (9), namely assuming a power-law dependence of  $\varepsilon_{vac}$  on  $R$  in the form  $\varepsilon_{vac} \sim R^{-\nu}$  with an undefined power index  $\nu$ , and then obtaining for the vacuum pressure the relation

$$p_{vac} = -\frac{3-\nu}{3} \varepsilon_{vac}. \quad (11)$$

Here so far all power indices, especially the cardinal index values  $\nu = 0, 1, 2, 3$ , were equally allowed, none of them being apriori excluded, however, the  $R$ -dependence of  $p_{vac}$  and  $\varepsilon_{vac}$  turned out to be identical.

If we now make use of these earlier results (Eq. (11), but try to find solutions of the extended thermodynamic Eq. (10) on the basis of these earlier findings we then obtain:

$$-\frac{4\pi}{3} \frac{3(3-\nu)}{3-\nu} p_{vac} R^2 = -3 \frac{4\pi}{3} p_{vac} R^2 + \frac{8\pi^2 G}{15c^4} \frac{d}{dR} [(\varepsilon_{vac} + 3p_{vac})^2 R^5] \quad (12)$$

which, since the terms left and right of the identity sign cancel, after replacing  $\varepsilon_{vac}$  by  $p_{vac}$  with Eq. (11) leads to the requirement

$$0 = \frac{(6-3\nu)^2}{(3-\nu)^2} \frac{d}{dR} (p_{vac}^2 R^5). \quad (13)$$

This equation for a completed thermodynamics now evidently is only solved by two special values of  $\nu$ , i.e. the requirements:

a:  $\nu = \nu_1 = 2$

and

b:  $p_{vac}^2 R^5 = \text{const}$ , i.e. by  $\nu = \nu_2 = 5/2$

thus now determining, compared to the earlier result, a much more restricted set of physically possible dependences of  $p_{vac}$  and  $\varepsilon_{vac}$  on  $R$ .

### 3 Do there exist two competing solutions?

From the above derivation the two solutions  $\nu = \nu_1$  and  $\nu = \nu_2$  are competing as equally justified, and one could think of taking a representation of the form

$$\varepsilon_{vac} = \varepsilon_{0,1} (R/R_0)^{-\nu_1} + \varepsilon_{0,2} (R/R_0)^{-\nu_2} \quad (14)$$

as the most general solution. However, without any concrete, specific physics behind the different forms, how  $\varepsilon_{vac}$  reacts to cosmic scale expansion, this form of a solution is not really satisfying. Thus we try to restrict the possible power indices even more by looking at this question from another view.

Requiring a universe where in every instant the positively valued vacuum energy is compensated by its gravitationally induced self-binding energy, then, in addition to the above thermodynamic requirement, one has to also fulfill the following relation (see Fahr & Heyl 2007a, 2007b) for a vanishing total vacuum energy

$$\frac{4\pi}{3} (\varepsilon_{vac} + 3p_{vac}) R^3 = \frac{8\pi^2 G}{15c^4} [(\varepsilon_{vac} + 3p_{vac})^2 R^5]. \quad (15)$$

We now solve this quadratic equation with respect to the pressure  $p_{vac}$  and get the following two solutions:

$$p_{vac,1} = -\frac{1}{3}\varepsilon_{vac} \quad (16)$$

and

$$p_{vac,2} = \frac{1}{3}\left(\frac{5c^4}{2\pi GR^2} - \varepsilon_{vac}\right). \quad (17)$$

Insertion of Eq. (16) or Eq. (17) into Eq. (10) results in both cases in one and the same differential equation for the energy density  $\varepsilon_{vac}$  given by:

$$\frac{d\varepsilon_{vac}}{dR}R + 2\varepsilon_{vac} = 0 \quad (18)$$

which has the unique solution:

$$\varepsilon_{vac} = \varepsilon_{vac,0} \frac{R_0^2}{R^2} \sim p_{vac,1,2} \quad (19)$$

with  $\varepsilon_{vac,0}$  the vacuum energy density at a scale parameter  $R_0$ , e.g. at the present cosmic time  $t_0$ . Using  $\varepsilon_{vac} = \rho_{vac}c^2$  we finally get from Eq. (19) for the associated cosmic mass density  $\rho_{vac}$  of a pure vacuum-energy-dominated universe which scales according to  $R^{-2}$ :

$$\rho_{vac} = \rho_{vac,0} \frac{R_0^2}{R^2}. \quad (20)$$

Similar results, however derived independently from very different theoretical reasons, have already been published by Basilakos (2009), Solà (2013), Basilakos et al. (2013) and Solà (2014). In these papers it has been discussed that strictly keeping to covariance requirements of the underlying general relativistic field equations one can allow for a time-dependence of the inherent cosmic vacuum energy density  $\rho_{vac}$  and, as a leading term, one should preferably consider the following time-dependence of the vacuum energy density  $\rho_{vac} = \rho_{vac,0} + \alpha \cdot H^2(t)$ , where  $H = H(t) = \dot{R}/R$  denotes the time-dependent Hubble constant within a Friedman-Lemaître cosmology. As the above authors emphasize, this new setting will help solving many outstanding problems in the present-day cosmology like triggering a smooth transition from an initial inflationary expansion powered by very strong vacuum energy density into a present-day smooth inflation at very low vacuum energy densities of the order of  $\rho_{vac,0} \simeq 10^{-29} g/cm^3$ .

A similar attempt to subject the field equations to more general scale-invariance requirements has led Scholz (2008) on the basis of a Weylian scalar-tensor theory also to a term which acts equivalent to vacuum energy density and which is varying with  $(1/R^2)$  exactly like derived in our above approach. The question may, however, come up here with concern to the justification of a scale-invariance requirement applied to the GRT field equations. Nevertheless, there are hints from many sides that a scale- or time-dependent vacuum energy term  $\rho_{vac} = \rho_{vac}(t)$  seems to make much sense in cosmology.

#### 4 Friedmann-Lemaître equations for a $R^{-2}$ -scaling of $\rho_{vac}$

The Friedmann equations provide a relationship between the cosmic scale  $R$ , its first and second time derivatives  $\dot{R}$  and  $\ddot{R}$  on one hand, and the cosmic mass density  $\rho$  and its associated pressure  $p$  on the other hand. In the following we investigate a pure vacuum energy filled universe with curvature  $K = 0$ . The Friedmann equations are then given by:

$$H^2(t) = \frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho_{vac} \quad (21)$$

and

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho_{vac}c^2 + 3p_{vac}) \quad (22)$$

with  $H(t)$  the time dependent Hubble parameter. Insertion of the  $R^{-2}$ -dependent equivalent mass density of the vacuum energy given by Eq. (20) into Eq. (21) leads to:

$$H^2(t) = \frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho_{vac,0} \frac{R_0^2}{R^2} \quad (23)$$

which provides the following result for the expansion velocity  $\dot{R}$  of the scaling factor  $R$ :

$$\dot{R} = \sqrt{\frac{8\pi G\rho_{vac,0}}{3}}R_0 = const. \quad (24)$$

and thus, if we require  $R(t=0) = 0$ :

$$R = \sqrt{\frac{8\pi G\rho_{vac,0}}{3}}R_0 t. \quad (25)$$

We now look at the 2. Friedmann equation Eq. (22). The calculated pressure in eq. Eq. (16) results in a cosmic acceleration which is simply zero:

$$\begin{aligned}\ddot{R} &= -\frac{4\pi G}{3c^2}(\rho_{vac}c^2 + 3p_{vac,1})R = \\ &= -\frac{4\pi G}{3c^2}(\rho_{vac}c^2 - 3\frac{1}{3}\rho_{vac}c^2)R = 0.\end{aligned}\quad (26)$$

However, the pressure in Eq. (17) leads to the following expression:

$$\begin{aligned}\ddot{R} &= -\frac{4\pi G}{3c^2}(\rho_{vac}c^2 + 3\frac{1}{3}\frac{5c^4}{2\pi GR^2} - \\ &= 3\frac{1}{3}\rho_{vac}c^2)R = -\frac{10c^2}{3R}.\end{aligned}\quad (27)$$

The result of Eq. (27) is in discrepancy with the constant expansion velocity  $\dot{R}$  in Eq. (24) which follows from the 1. Friedmann equation which itself does not depend on the pressure. Thus, since a constant  $\dot{R}$  cannot be realized with Eq. (27), we can conclude that the pressure in Eq. (17) and its associated acceleration in Eq. (27) are of course mathematical solutions of our thermodynamical equations but not physical ones which are realized in a cosmos with a vacuum energy density which scales according to  $R^{-2}$  and which always leads to  $\dot{R} = const.$ , i.e.  $\ddot{R} = 0$ . With other words, the correlation between a vacuum energy density  $\epsilon_{vac} \sim R^{-2}$  and its associated pressure  $p_{vac}$  is given by (equation of state):

$$p_{vac} = -\frac{1}{3}\epsilon_{vac}.\quad (28)$$

## 5 Consequences of the $R^{-2}$ -scaling of $\rho_{vac}$ and conclusions

With the results of the previous chapter for a matter-free, empty universe dominated by pure vacuum energy and with a curvature parameter  $K = 0$  (i.e. a flat vacuum universe) we now look at the Hubble parameter  $H(t)$  which is given for this universe by (see Eqs. (24) and (25):

$$H(t) = \frac{\dot{R}}{R} = \frac{\sqrt{\frac{8\pi G\rho_{vac,0}}{3}}R_0}{\sqrt{\frac{8\pi G\rho_{vac,0}}{3}}R_0t} = \frac{1}{t}\quad (29)$$

and for the present cosmic time  $t_0$  leads to  $t_0 = 1/H_0(t_0) \approx 1,37 \cdot 10^{10} yrs$  with the presently accepted Hubble parameter  $H_0 \approx 72 km/s/Mpc$  (see Bennett et al. 2003).

Furthermore, we can now try to calculate the equivalent of the total, global vacuum energy content of the universe, i.e. the mass content  $M_{vac}$  of such an universe assuming that the extension of the visible universe is given by the so-called Hubble radius  $R_H$ , defined as that cosmic distance where the cosmic recession velocity  $\dot{R}$  equals the velocity of light  $c$  and given by:

$$R_H = \frac{c}{H(t)} = ct\quad (30)$$

with  $H(t)$  given by Eq. (29). Now, in addition Eq. (21) leads us to the cosmic density:

$$\rho_{vac} = \frac{3H^2}{8\pi G} = \frac{3}{8\pi Gt^2}\quad (31)$$

which is nowadays ( $t = t_0$ ):

$$\rho_{vac,0} = \frac{3H_0^2}{8\pi G} = \frac{3}{8\pi Gt_0^2} \approx 10^{-26} \frac{kg}{m^3}.\quad (32)$$

Hence we can express the present vacuum mass of the universe by:

$$\begin{aligned}M_{vac} &= \frac{4\pi}{3}\rho_{vac,0}R_H^3 = \frac{4\pi}{3}\frac{3}{8\pi Gt_0^2}c^3t_0^3 = \\ &= \frac{c^3}{2G}t_0 \approx 10^{53}kg \approx 10^{80}m_p\end{aligned}\quad (33)$$

with  $m_p$  as the mass of the proton. Interestingly, the Eqs. (32) and (33) show well-known numbers, quite familiar to nowadays astronomers, namely just numbers for the presently assumed critical mass density of our universe and the present mass content of the visible universe, respectively. This may in first glance appear to be completely casual and be highly astonishing, since with the above we calculated density and mass of a cosmic vacuum on the basis of a  $R^{-2}$ -scaling vacuum energy density, while the numbers that we got are typical for the matter content of our present universe.

These above results are, however, not judged by the authors of this paper to be an numerical artifact, but may have the following important reason: We can take Eq. (20) to calculate the equivalent mass density of the vacuum energy density of the very early universe, i.e. at the Planck time  $t_p$  or the Planck length  $R_H(t_p) = r_p = ct_p$ , thereby expressing the reference scale  $R_0$  by the present Hubble radius  $R_{H,0} = ct_0$  (according to Eq. (30)) and get:

$$\rho_{vac}(r_p) = \rho_{vac}(t_p) = \rho_{vac,0} \frac{R_{H,0}^2}{r_p^2} =$$

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$$\rho_{vac,0} \frac{ct_0^2}{ct_p^2} = \rho_{vac,0} \frac{t_0^2}{t_p^2}. \quad (34)$$

If we now substitute  $\rho_{vac,0}$  by  $3/8\pi G t_0^2$  (ref. Eq. (32)) then Eq. (34) can be written as:

$$\rho_{vac}(r_p) = \rho_{vac}(t_p) = \frac{3}{8\pi G t_0^2} \frac{t_0^2}{t_p^2} = \frac{3}{8\pi G t_p^2}. \quad (35)$$

When we replace the Planck time  $t_p = r_p/c = \sqrt{\hbar G/c^5}$  we finally get the following formula:

$$\rho_{vac}(r_p) = \rho_{vac}(t_p) = \frac{3}{8\pi} \frac{c^5}{\hbar G^2} = \rho_p \quad (36)$$

which is identical to the Planck density  $\rho_p$  defined by the ratio of a half Planck mass  $\frac{1}{2}m_p = \frac{1}{2}\sqrt{\hbar c/G}$  and the Planck volume  $\frac{4\pi}{3}r_p^3$  with the Planck length  $r_p = \sqrt{\hbar G/c^3}$ . This means that the equivalent vacuum mass density which scales according to  $R^{-2}$  in our model can be described as a scaling Planck density  $\rho_p$ . In fact, we can re-write Eq. (31) by replacing the factor  $3/8\pi G$  using Eq. (36) and get:

$$\rho_{vac}(t) = \frac{3}{8\pi G t^2} = \rho_p \frac{\hbar G/c^5}{t^2} = \rho_p \frac{t_p^2}{t^2} \quad (37)$$

where the Planck time  $t_p = \sqrt{\hbar G/c^5}$  is now the reference time. The ratio  $\rho_{vac,0}/\rho_p$  is then simply given by:

$$\frac{\rho_{vac,0}}{\rho_p} = \frac{t_0^2}{t_p^2} \approx \cdot 10^{-122} \quad (38)$$

and also is a well-known discrepancy factor with respect to the ratio of the present vacuum mass density on one hand and the theoretical value of the vacuum mass density that follows from field-theoretical calculations on the other hand (Zeldovich 1968; Weinberg 1989). Thus we can conclude, that this discrepancy vanishes for a vacuum energy density that scales according to  $R^{-2}$  as shown in this paper.



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